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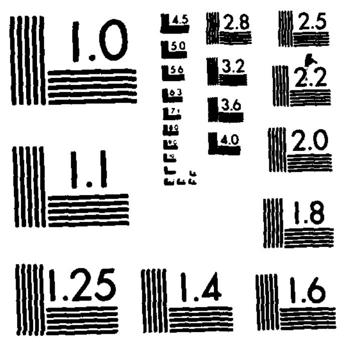

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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

SEAKEEPING OPTIMIZATION

by

David A. Walden

and

Peter Grundmann

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

SHIP PERFORMANCE DEPARTMENT

May 1985

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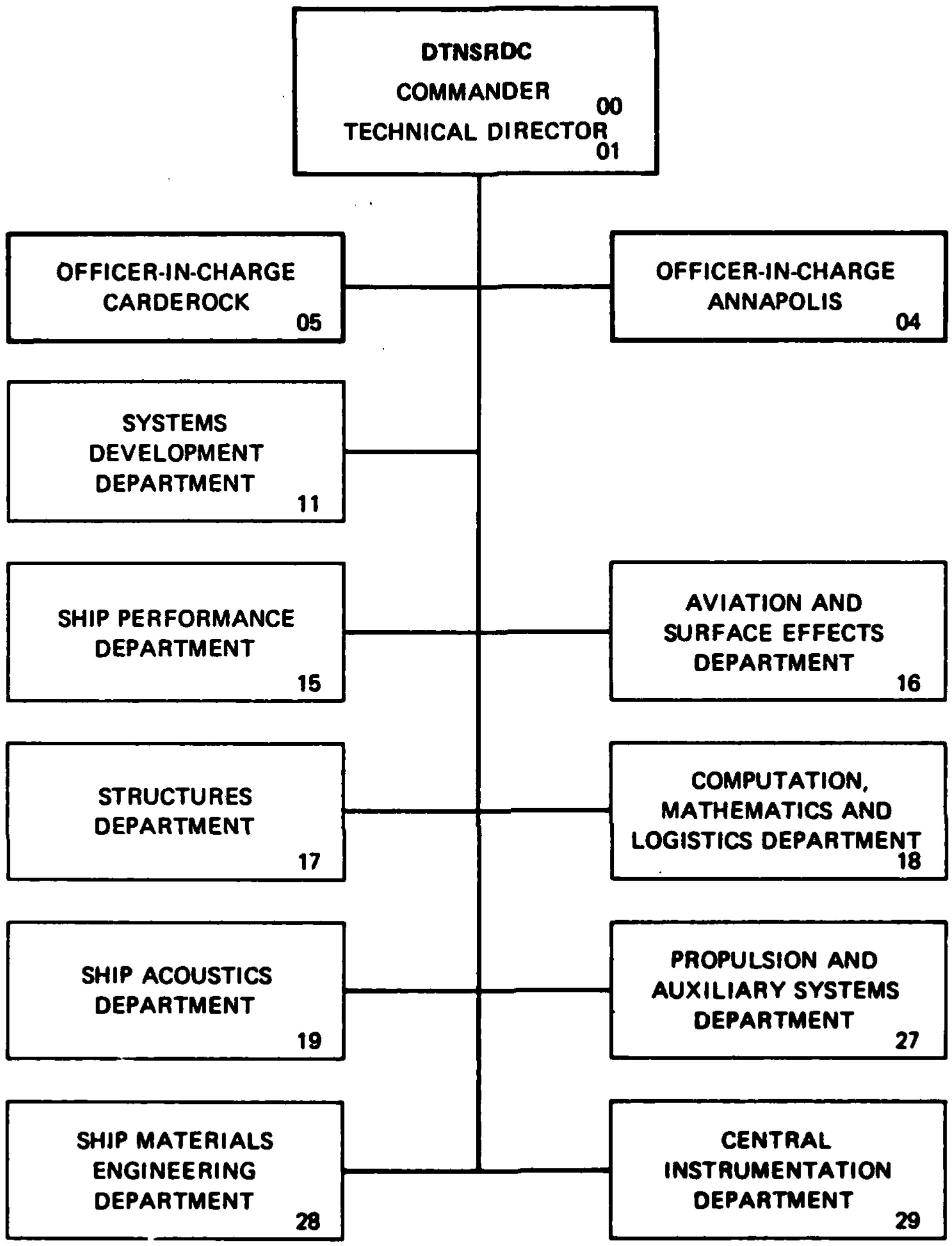

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It is concluded that optimization methods can be used in the early stages of design to develop hull forms with superior seakeeping.

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NOTATION

B	Beam (m)
C_M	Midship section coefficient
C_{PA}	Prismatic coefficient of afterbody
C_{PF}	Prismatic coefficent of forebody
C_{VPA}	Vertical prismatic coefficient of afterbody
C_{VPF}	Vertical prismatic coefficient of forebody
C_{WA}	Waterplane coefficient of afterbody
C_{WF}	Waterplane coefficient of forebody
DWL	Design waterline
GM	Distance from center of gravity to metacenter (m)
g	Acceleration of gravity (m/sec^2)
KG	Distance from keel to center of gravity (m)
L	Length (m)
T	Draft (m)
T_o	Modal wave period (sec)
T_ϕ	Calculated roll period (sec)
σ	Sectional area coefficient
Δ	Displacement

ABSTRACT

An application of optimization methods to the design of hulls with the goal of improving seakeeping is described. The seakeeping calculation technique as well as the means of generating the hull form descriptions from given sets of coefficients are outlined. A short discussion explains the selection of a critical wave height as a measure of seakeeping. Examples are given to show the influence of the structural and stability constraints on the hull forms generated. The variation of seakeeping with the hull form parameters is shown. Results are presented for optimizations at 10, 20, and 30 knots.

It is concluded that optimization methods can be used in the early stages of design to develop hull forms with superior seakeeping.

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INTRODUCTION

Designing hull forms with superior seakeeping performance demands basic information about the correlation between hull form parameters and ship motions. One method of obtaining this information is through model tests.

Classical model testing is still seen to be the most accurate way to get information about wave induced ship motion characteristics for hull design. But because of the time and cost, the number of considered hull form variations is always very limited. In most cases the complete test series covers less than 10 different configurations. Consequently, the results can only offer limited data on trends. Each of the trends depend on: (a) the parent hull form, (b) the kind and number of simultaneously varied hull form parameters and (c) the overall parameter ranges. Therefore, their significance is, to some extent, uncertain. Although the results of model tests are more accurate than those of theoretical predictions, the trends from model test results may lead to misinterpretations because of the comparatively small amount of data. Since these trends are especially important for the selection of hull form parameters in the early design stage, their prediction is more critical than the accuracy of single data points.

Bales[1*], with the intention of avoiding the difficulties connected with model tests and based on good results from theoretical prediction methods for the head sea case, tried a quite different way of finding an optimum seakeeping design. It ~~He~~ calculated ship motions for 20 normalized frigate/destroyer hulls and used the significant amplitudes of 8 motion-related quantities to create a ranking number. With a regression analysis, he combined the ranking number with those hull form parameters which, in his opinion, govern the seakeeping performance. Finally, he obtained an estimation equation for the ranking number which allows the comparison of the seakeeping performance of different hulls. The estimation equation indicates by its coefficients whether the various selected hull form parameters should be as large or as small as possible. The original work of Bales has been extended by McCreight[2] and by Walden[3] to include additional hull forms parameters. For a designer these equations offer some trends similar to the results of model tests but still do not help in getting reasonable combinations of parameters. The situation gets worse if one desires to consider hulls with hull form parameters outside the ranges of already existing hulls.

Recent research on hull form variation to improve the seakeeping performance has been done by Schmitke and Murdey[4] in the experimental field, by Loukakis, et al.[5] and Blok and Beukelman[6] using a calculation approach, and by Bau[7] using a combination of both. In all cases, the number of considered variations was limited. Therefore an optimization approach using calculated results for a very large number of hull form variations was thought to be very useful.

An optimized seakeeping design can be achieved by a systematical computer based performance calculation covering extended parameter ranges independent of constraints given by existing designs. Among the optimization alternatives are:

- Search for a hull form with optimum seakeeping performance, i.e., maximum range of operability under the assumption of a fixed displacement, a constant speed, and a given set of motion criteria.
- Search for a hull form with minimized displacement under the assumption of a required wave height (sea state), a constant speed, and a given set of motion criteria.

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*A complete listing of references is given on page 12.

The present paper covers the investigation on the first alternative, i.e., maximization of the critical wave height for a given displacement-speed combination.

There were five major problems to face when starting the optimization procedure:

- The optimization procedure has to be powerful enough to find the global optimum even if the multidimensional field of possible solutions is not unimodal.
- The seakeeping calculation, since it is repeated for a large number of combinations, has to be very fast in order to keep the whole procedure within reasonable time/cost limits.
- A means of generating sufficiently detailed hull form descriptions is required.
- A cost-function, which will be minimized during the optimization procedure, has to be created. In our case, it has to include an indicator of the seakeeping performance.
- Constraints have to be found to make sure that the hulls under investigation meet basic structural and stability requirements.

OPTIMIZATION PROCEDURE

All optimization procedures use one of two basic approaches, random or direct search. Both approaches were used during the course of this work. The exponential random search, a refinement of random search, is described by Mandel and Leopold[8] and by Gray[9]. This method can be considered reliable in that it is very likely to find the global optimum. The method starts with a random search over the entire variable ranges and then progressively concentrates its search closer and closer to the combination of variables giving the best result. This method is useful in that it can provide a distribution of the variables over their ranges making it possible to look for trends and see the effect of constraints on variable ranges.

The advantage of direct search is that the optimum can be found with fewer function evaluations than with random search, the disadvantage is that it requires unimodality. Having found through random search that the cost function appeared to have only one well defined maximum, the direct search method of Hooke and Jeeves[10] as described by Parsons[11] was used.

SEAKEEPING CALCULATION

The time consuming portion of a seakeeping calculation is the station by station computation of added mass and damping over a range of frequencies. As described by Grim[12], the calculations for Lewis-forms[13] are considerably more efficient than those required for more general hull forms. In fact, sufficiently accurate approximations exist,* which further improve the efficiency of the calculations.

HULL FORM DEVELOPMENT

For generating a hull form description to the level of detail necessary to carry out seakeeping calculations, i.e., for providing beam, draft, and sectional area curves, a method very similar to that described in References 14 and 15 was used. Seventh order polynomials were used for the beam and sectional area curves. The boundary conditions for the polynomials include conditions to produce curves with the desired C_{PA}, C_{PF}, C_{WA} and C_{WF}.

Although a ship produced by this method has the desired values for L, T, Δ, C_{PA}, C_{PF}, C_{WA}, C_{WF}, and C_M, it still is not the only possible ship with these specific parameter values. Ships can have the same C_{PA} and C_{PF} but different sectional area curves. It has been found, however, that there are no significant differences in seakeeping performance between ships as long as they have the same values for the above mentioned principal dimensions and hull form parameters.

COST-FUNCTION

The optimization of a hull form with the intention of improving the ship's behavior in severe sea states requires an indicator of the seakeeping performance. Seakeeping performance, however, has no single definition. Based on the actual problem, it can cover different combinations of motion and motion related quantities. Recent work on this subject has been done by Kehoe et al.[16] and Kim et al.[17]. Bales[1], in a first approach to quantify the seakeeping performance, chose eight ship responses, all for long-crested head seas. With his transformation of normalized significant amplitudes into a ranking number and with his estimation equation for this number, he created a first easy to use seakeeping performance indicator.

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*As described in unpublished work by L. Ravenscroft at DTNSRDC.

For the motion calculation in the present procedure it was also decided to retain the restriction to the head sea case, assuming that roll motion can be effectively reduced by proper bilge keel design and/or the use of antiroll fins. Nevertheless, Bales' estimation for the ranking number has not been used. The reasons are:

- The considered hull form parameters in Bales' original work do not all equally influence the seakeeping performance, and there are additional parameters which do have influence.
- The accuracy of Bales' estimation equation, see Reference 1, depends on the data base used.
- Varying the hull form parameters can increase some motions while simultaneously decreasing others. Thus, the result of an optimized Bales ranking number is actually a minimized average over the motion amplitudes. This would be acceptable if all of the motions were of the same importance which, in fact, was Bales' basic assumption. But for state-of-the-art warship design, the importance of the various motions are seen to be quite different. They are governed by equipment and mission-oriented motion criteria.

Motion criteria, together with calculated significant motion amplitudes, lead to maximum acceptable wave height for each of the considered ship motions. The lowest of these wave heights indicates which response actually limits the ship's operability. For the optimization, only the significant amplitude of this specific response has to be reduced to improve the operability. Even if other significant amplitudes get worse, it has no effect as long as they have higher maximum wave heights. The lowest of all the maximum wave heights is called the critical wave height.

Since the ship response which defines the critical wave height can differ with the modal wave period, the calculation was extended to consider five different periods. The average of the resulting five critical wave heights was taken as the measure of seakeeping performance. As an example, periods of 10, 12, 14, 16, and 18 seconds were chosen based on wave height/period statistics in Reference 18. Maximizing the average value leads to a critical wave height envelope over the period range which can be ruled by several, if not by all, of the selected responses indicating a quite balanced solution. The resulting optimum provides maximum operability under the assumption that all wave height/wave period combinations are equally weighted.

The choice of equal weighting follows from the intention to demonstrate the process of seakeeping optimization while keeping the assumptions and constraints simple and yet reasonable. In any actual optimization, the wave height/period weightings should be based on statistics for the operating area and season of interest.

The wave height calculation covers pitch, vertical acceleration at midship and at the forward perpendicular as well as slamming. The motion criteria used for the presented results are:

- Maximum significant single amplitudes for

Pitch	3°
Vertical acceleration at midship	0.4g
Vertical acceleration at forward perpendicular	0.55g

- Maximum probability of slamming at Station 3 0.03

where the definition of slamming is that given by Ochi and Motter[19].

CONSTRAINTS

The majority of combinations of randomly selected hull form parameters led to unreasonable hull forms even if the ranges of the hull form parameters only cover values of existing ships. It is even more true if parameter ranges are extended to find solutions outside the conventional field. Hulls are found with extreme L/B and B/T values, with unacceptable bulbous sections, and with unreasonable waterline or section area curves. To avoid these, a number of constraints are required:

- The normalized section area and waterline curves have to be fair and to remain between 0 and 1 over the whole ship length. This affects strongly the possible $C_{PA} - C_{PF}$ and $C_{WA} - C_{WF}$ combinations.
- The seakeeping calculation used requires hull forms which are described by regular two parameter Lewis forms. With checks on the sectional area coefficients, all tunneled or bulbous sections are rejected. (Reference 20)
- To provide adequate longitudinal strength, the ranges for L/T, B, and B/T are limited.

$$20 \leq L/T \leq 35$$
$$L/10 \leq B \leq L/10 + 6.1$$
$$2.9 \leq B/T \leq 4.1$$

  All ranges are in accordance with existing data for frigates and destroyers as well as with guidelines for early design steps, see Reference 21.

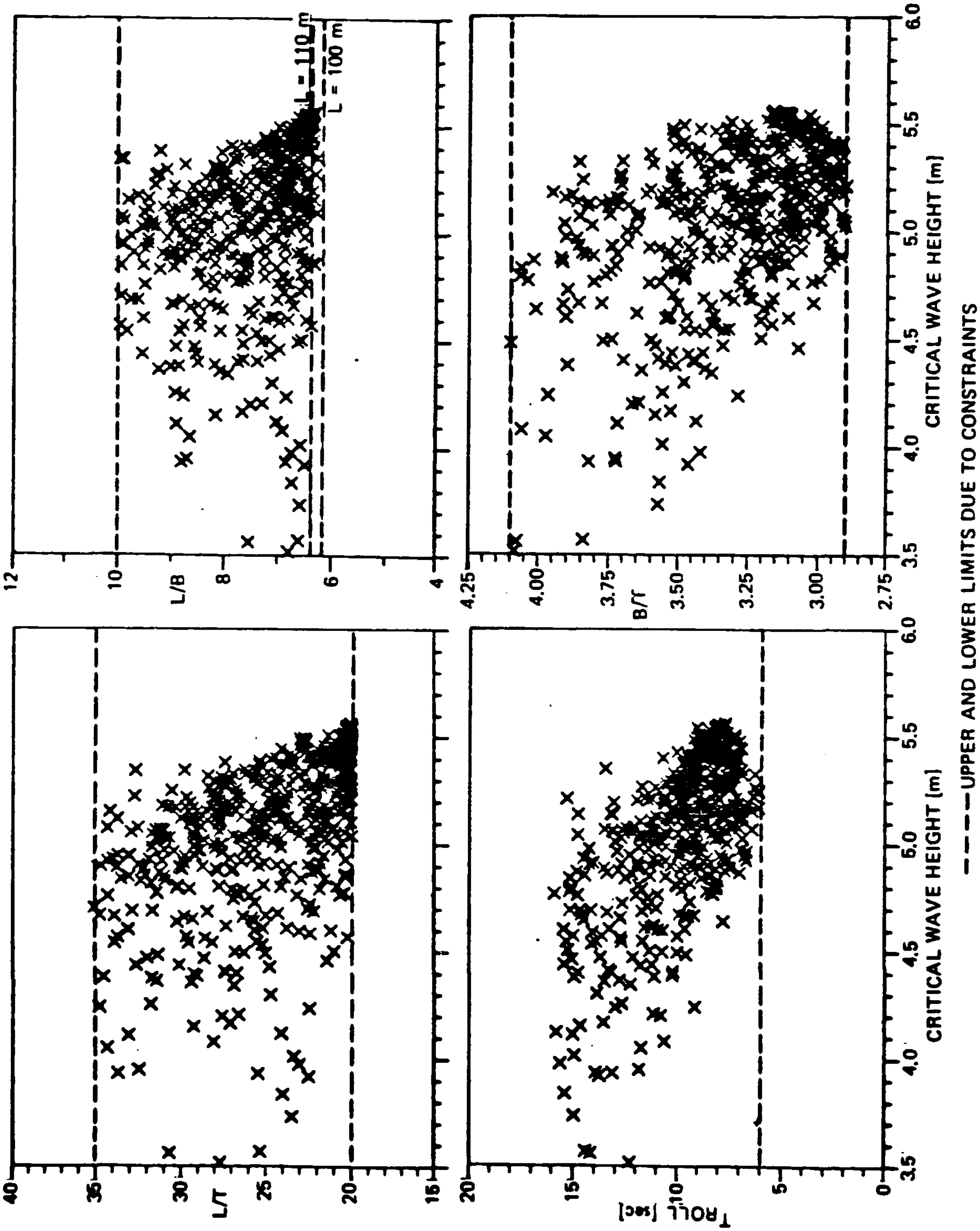

Figure 7 - Influence of Constraints on the Optimization Result

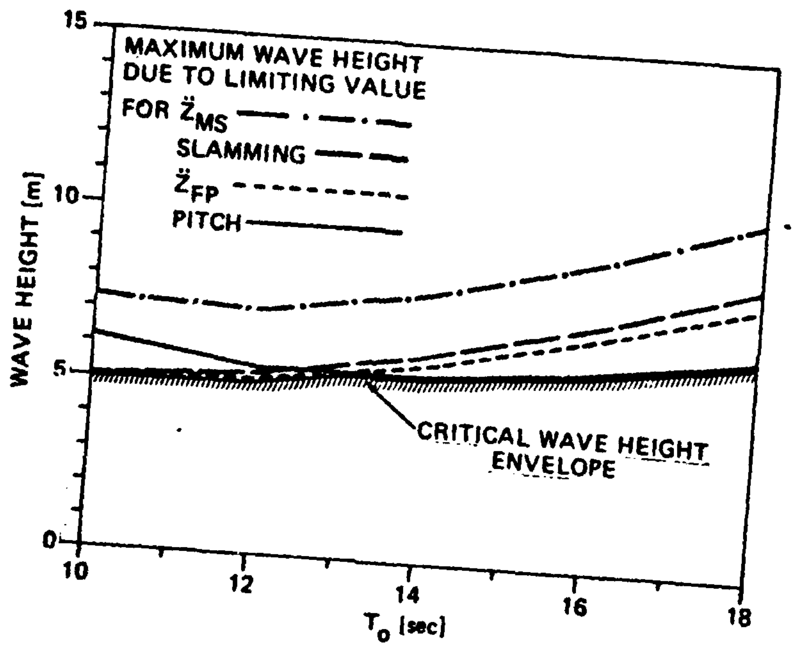

Figure 6 - Distribution of Maximum Wave Heights for the Optimum Hull

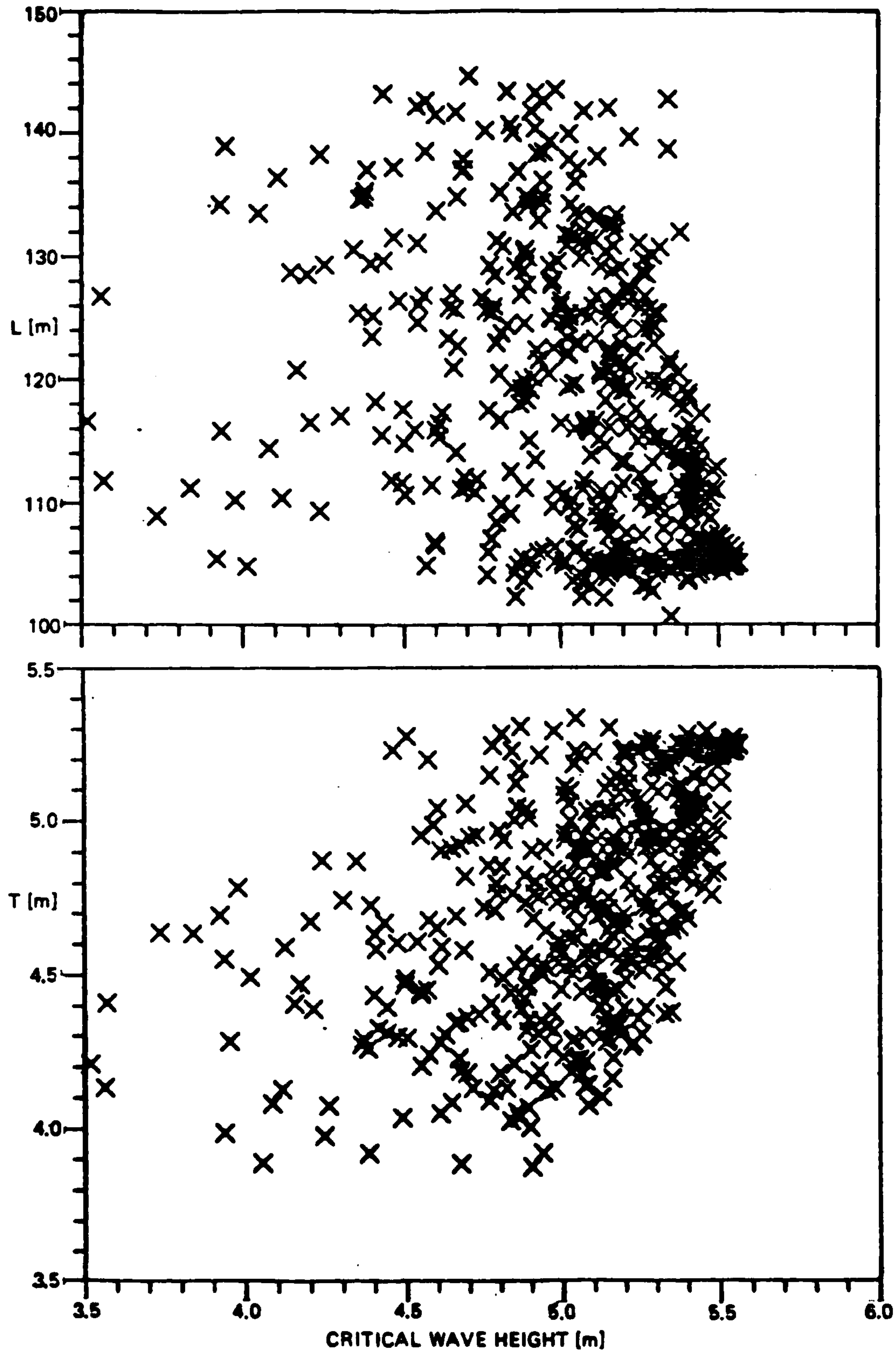

Figure 5 - L and T versus Critical Wave Height

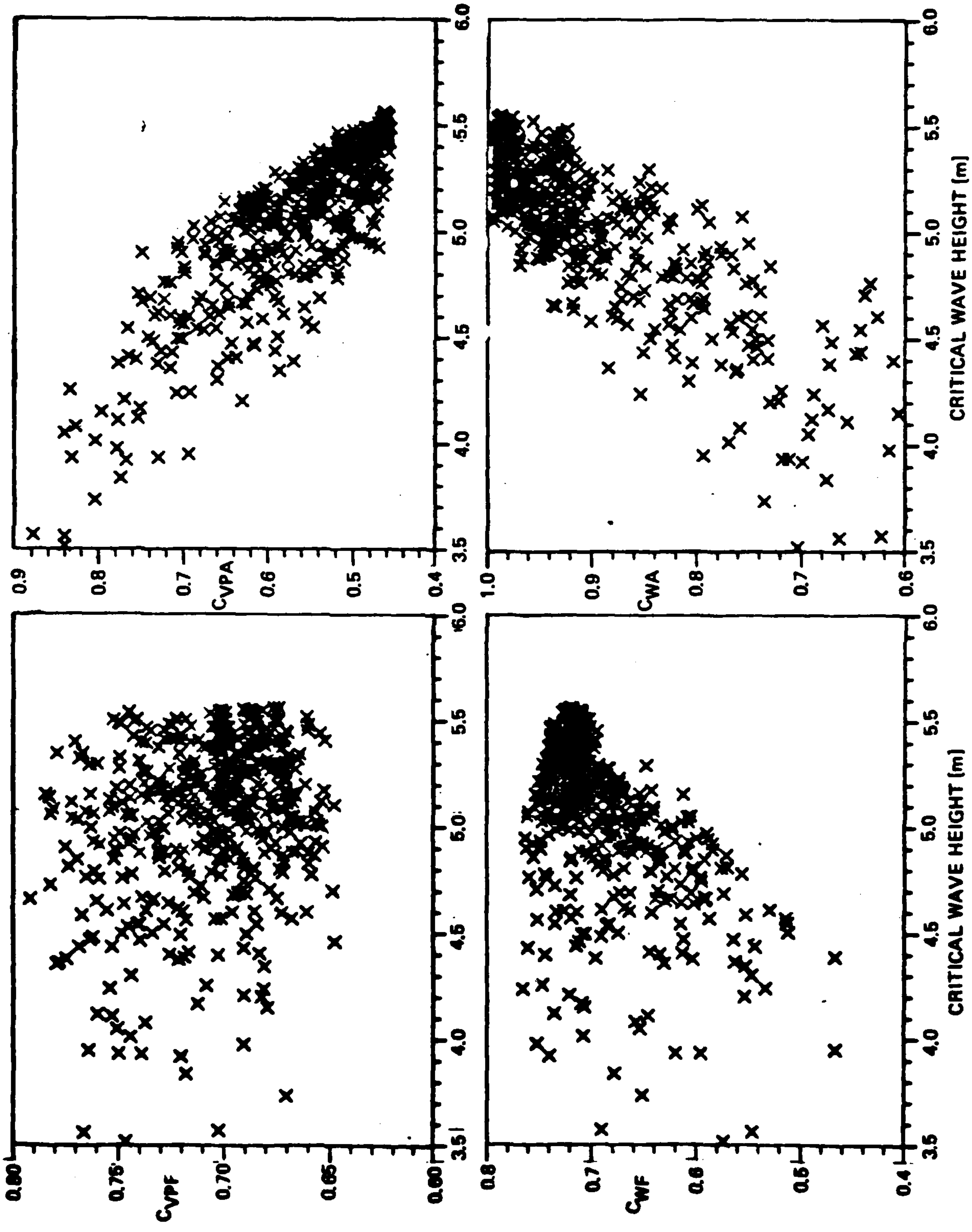

Figure 4 - Hull Form Coefficients versus Critical Wave Height

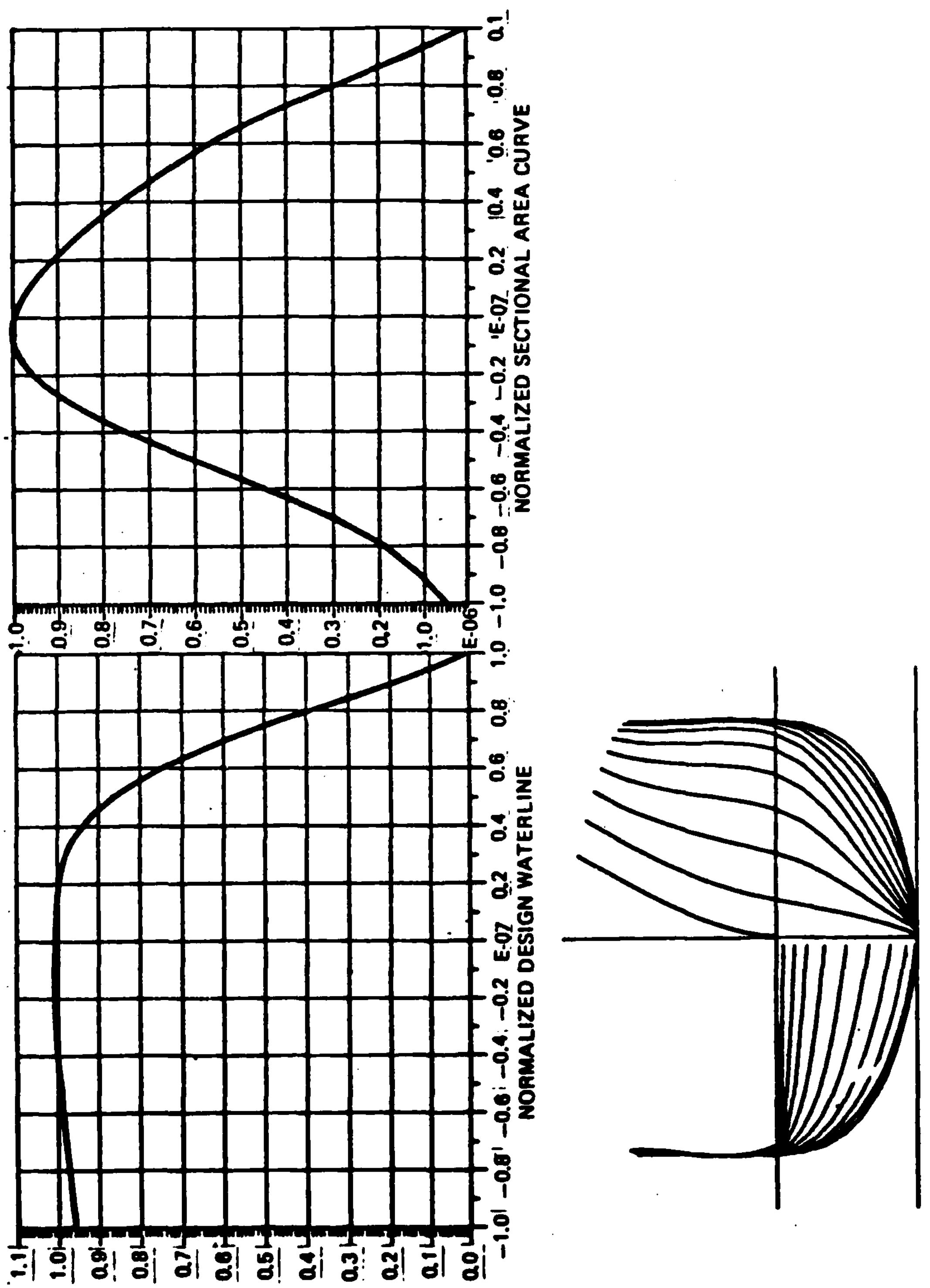

Figure 3 - Optimum Hull

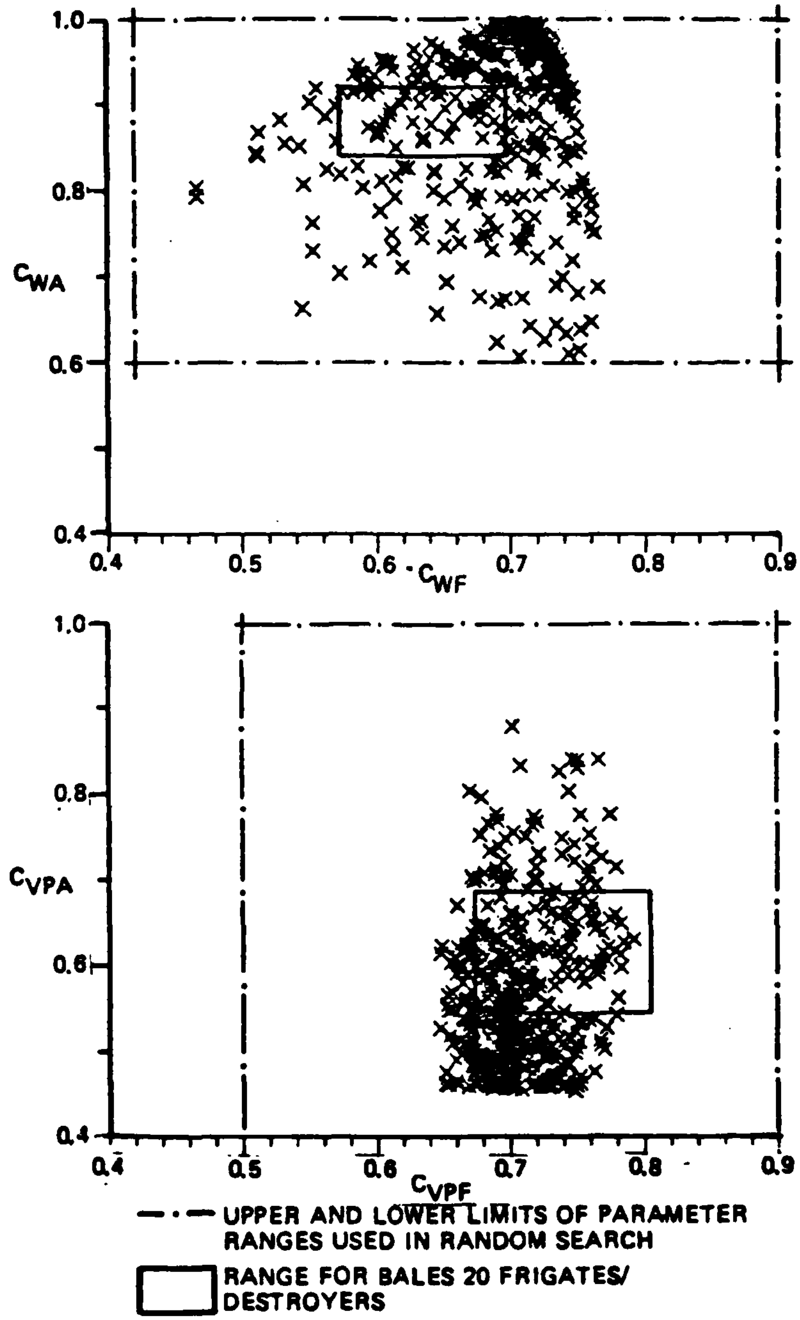

Figure 2 - Ranges for C_{WF}, C_{WA}, C_{VPF}, C_{VPA}

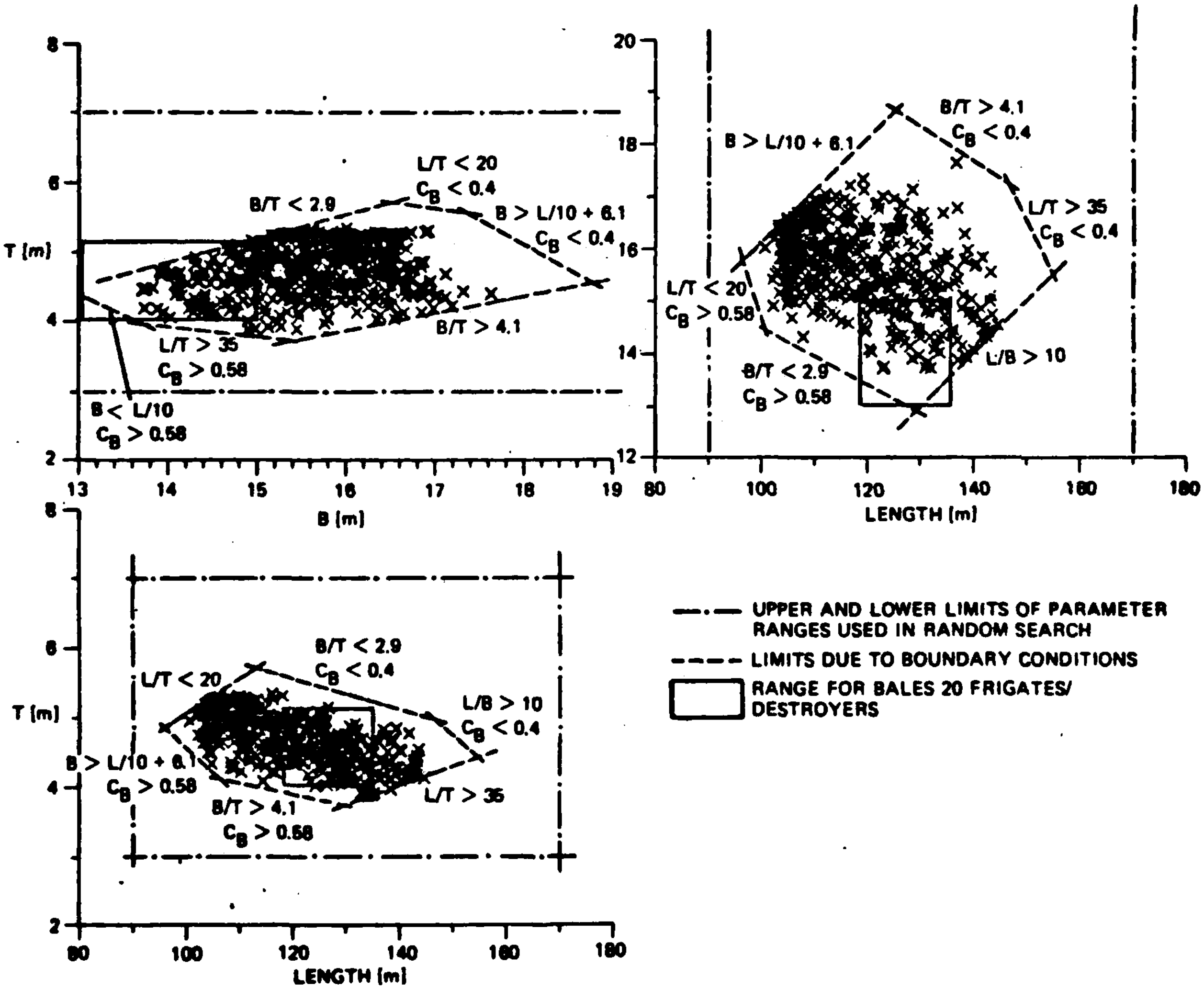

Figure 1 - Ranges for L, B, T

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speed. The 20-knot ship is limited by pitch at 10 and 20 knots but then by slamming at 30 knots. Slamming for both ships increases (limiting wave height decreases) with ship speed. Thus since different motions govern the performance for the two ships, the trends in critical wave height are opposite while the trends of both pitch and heave are the same for the two ships.

CONCLUSION

The application of optimization methods to the design of hull forms with superior seakeeping has shown useful results even though the optimum hull forms are based only on a limited number of relatively simple constraints. The method, however, can very easily be extended to include other hull form constraints and additional terms in the cost function. An obvious addition would be some measure of resistance.

In summary, as shown, optimization methods can provide guidance and suggestions to the hull form designer in the early stages of design on ways to improve seakeeping.

INFLUENCE OF SHIP SPEED ON OPTIMIZATION RESULTS

The results of optimization runs using the same set of motion criteria, the same displacement but with speeds of 20 and 10 knots are listed together with the 30-knot results in Table 2.

TABLE 2 - HULL FORM PARAMETER OF OPTIMUM SHIPS

	10-Knot Ship	20-Knot Ship	30-Knot Ship
C_{WF}	0.686	0.681	0.719
C_{WA}	0.965	0.938	0.986
C_{VPF}	0.664	0.664	0.674
C_{VPA}	0.470	0.475	0.464
T	4.26	4.26	5.25
C_M	0.8	0.8	0.8
Length	149.00	149.01	105.10
Displ.	4300.00	4300.00	4300.00
B	15.04	15.08	16.57

Major differences can be seen in the ship length. In opposition to the 30-knot case, the ship length for both the 20- as well as the 10-knot case shows a strong trend with the critical wave height, indicating that increase in ship length improves the seakeeping performance. C_{WA}, C_{WF}, C_{VPF} and C_{VPA} remain approximately the same for all three speeds. Body plans as well as sectional area curves and design water lines for the 30-knot, 20-knot, and 10-knot optimum are shown in Figures 8 and 9.

A comparison of the critical wave height distribution over the speed range of the three different optima (Figure 10) indicates that the 30-knot ship is only superior at the high ship speed. For a speed of less than 25 knots, the 20- and 10-knot ships which are characterized by their greater length, smaller draft and smaller beam show much better performance.

The trend of increasing performance with increasing speed for the 30-knot ship can be explained by reference to Figure 11. Here it can be seen that the performance of the 30-knot ship is limited by pitch over the entire speed range. Pitch for both ships decreases (limiting wave height increases) with increasing ship

- Length should be decreased to improve the slamming behavior which actually indicates that T should be increased (moderate trend)
- Length has no influence on the vertical acceleration at the forward perpendicular

The strong trend with the heave acceleration is of minor importance. Because of the chosen motion criteria, heave acceleration has no influence on the ship's operability. It is slamming together with pitch which limit the critical wave height. Since pitch and slamming show contrary trends with the ship length, the length does not correlate with the critical wave height at all. For other motion criteria, the results might be quite different. Since it seems to be necessary to use equipment and mission-oriented motion criteria to optimize a hull form, the results are strongly connected with these criteria and are difficult to generalize. Resulting trends might follow those of other investigations but they don't have to.

The comparatively strong correlation between C_{VPA} and the critical wave height reflects the high correlation between C_{VPA} and pitch combined with the high criteria-based influence of pitch on the critical wave height. C_{WF} and C_{WA} seem to be independent of any motion criteria set. Both tend to be as large as possible for all considered motions, which is in good agreement with the results of former investigations. C_{VPF} shows no tendency at all. Increased T corresponds to reduced slamming as expected. Increased T also corresponds to increased heave acceleration. T shows little relation with acceleration at the FP or with pitch.

For the optimum hull configuration, the area under the critical wave height envelope, which represents the ship's operability, reached its maximum. Figure 6 shows the distributions of the maximum wave heights for the four considered ship responses over the modal wave period range. The fact that three of four responses influence the critical wave height envelope indicates that the optimization procedure leads to a well balanced design, i.e., the resulting hull represents a good balance between decreasing slam performance to improve pitch performance, decreasing pitch performance to improve acceleration performance, etc.

The influence of the constraints on the result can be seen in Figure 7. The optimum hull configuration reaches the constraint given by the lower limit for L/T and by the upper limit for L/B.

ship speed of 30 knots, and the set of motion criteria previously described. The hull form parameter of the optimum together with the upper and lower parameter limits are listed in Table 1.

TABLE 1 - OPTIMIZATION RESULTS
(Δ = 4300 t, V = 30 knots, C_M = 0.8)

	Optimum	Lower Limit	Upper Limit
C_{WF}	0.719	0.400	0.900
C_{WA}	0.986	0.600	1.000
C_{VPF}	0.674	0.500	0.900
C_{VPA}	0.464	0.350	1.000
L (m)	105.096	90.000	170.000
T (m)	5.245	3.000	7.000
B (m)	16.567	---	---

Figure 3 shows the resulting body plan. Figures 4 and 5 show the different dependencies of the critical wave height upon the hull form parameters. Each contains data points for 495 reasonable hulls out of an overall number of 175,000 considered combinations. The reason for this high number is to get clear pictures of ranges and trends. It has been found that the exponential random search method actually needs 7000 combinations, i.e., about 100 reasonable hulls to find the optimum. With the direct search method the same optimum was found in only 40 steps out of 100 checked combinations. The two methods differ by a factor of 2 in the number of calculations for reasonable hulls, but by a factor of 70 in the number of tried combinations. For the calculation time this has less effect because most of the unreasonable combinations are rejected during the first very easy checks requiring little calculation time. The factor of 2 however depends on properly chosen variable ranges for the exponential random search as well as on a reasonable starting point for the direct search method.

The most surprising result was that at 30 knots there is little relation between wave height and ship length. As can be seen in Figure 5, there are ships with lengths of 104 m and 145 m which both have critical wave heights of 5.5 m. A closer look at the wave height - ship length relationship for each of the four motions shows the following tendencies:

- Length should be increased to reduce heave acceleration (strong trend)
- Length should be increased to reduce pitch (relatively weak trend)

- With an estimation for KG, a roll period, T_ϕ, is calculated. The period is required to be greater than 6 seconds which marks an upper limit for the GM value. The smallest GM value allowed is 0.04 x B. (Reference 21)

Using these constraints, various hull forms were found with relatively small flare angles relative to horizontal at the waterline near the bow. An investigation on this problem showed that flare angles of less than 30 degrees appeared which would cause extreme vertical acceleration and serious problems due to bow flare slamming. It was decided to limit the minimum flare angle to 50 degrees, which leads to the following functional dependency of the sectional area coefficient, σ on T/B.

$$\sigma > - 0.5\ T/B + 0.77$$

Hulls which failed this test at any of the forward stations were not further considered.

The hull form generation method derives the profile curve from the sectional area coefficient curves. Resulting hulls can have very flat aft sections with a profile curve running nearly parallel to the DWL over about 1/10 of the ship length. Like the extreme bow flare, this would cause slamming problems. Since there is no generally agreed upon value for the aft slope of the profile curve, it has been fixed at 1.6 T/L.

INFLUENCE OF CONSTRAINTS ON THE PARAMETER RANGES

To find reasonable ranges for the considered hull form parameters and to get information about the influence of the chosen constraints, an investigation was made using extended parameter ranges. The calculations were based on a fixed displacement of 4300 tonnes, to make the results comparable to Bales' 20-hull data bases. The ranges determined by the constraints, the given parameter limits, as well as the comparatively small ranges covered by the data of the Bales' 20-hull data bases are shown in Figures 1 and 2. The results indicate that it is at least possible to meet all the constraints even with unconventional parameter combinations.

OPTIMIZATION RESULTS

After the calculation procedure and the constraints proved their reliability, an optimization was performed for the same fixed displacement of 4300 tonnes, a

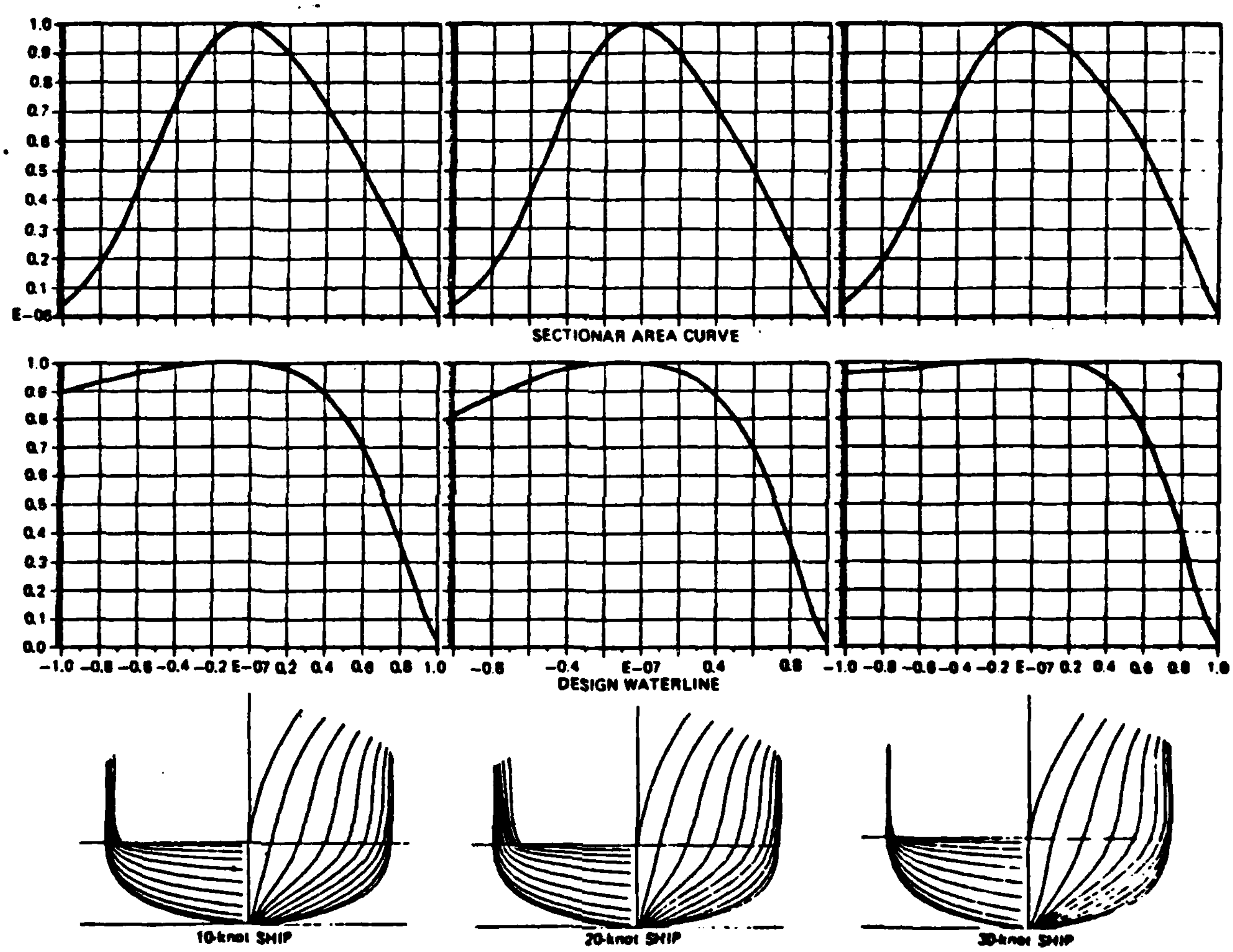

Figure 8 - Optima for 10, 20, and 30 Knots

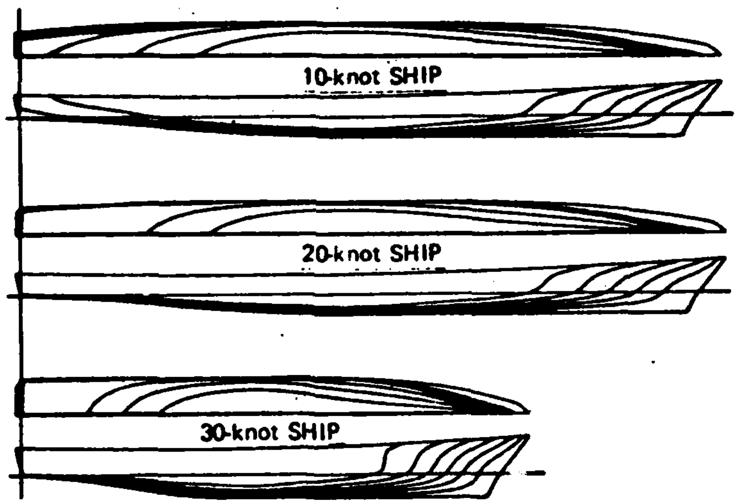

Figure 9 - Profiles and Plans of Optimum Hulls

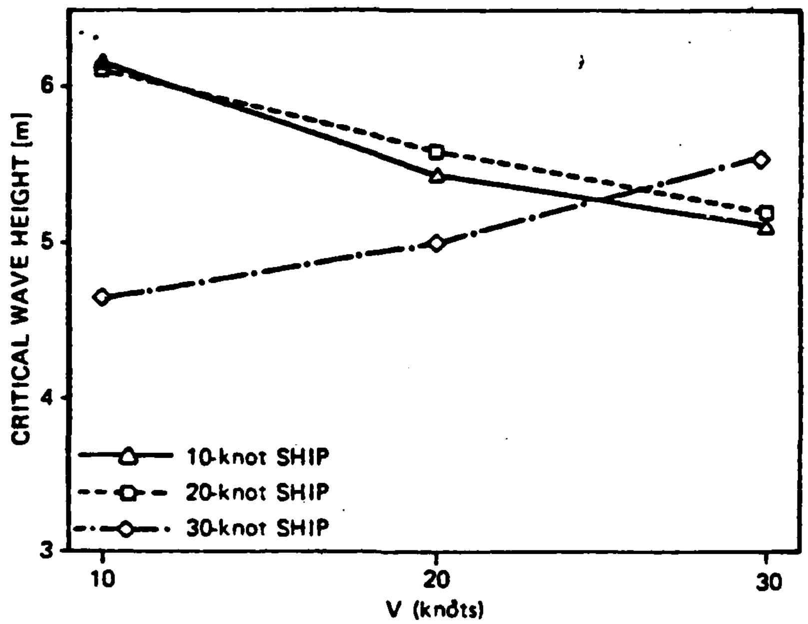

Figure 10 - Critical Wave Height versus ship speed

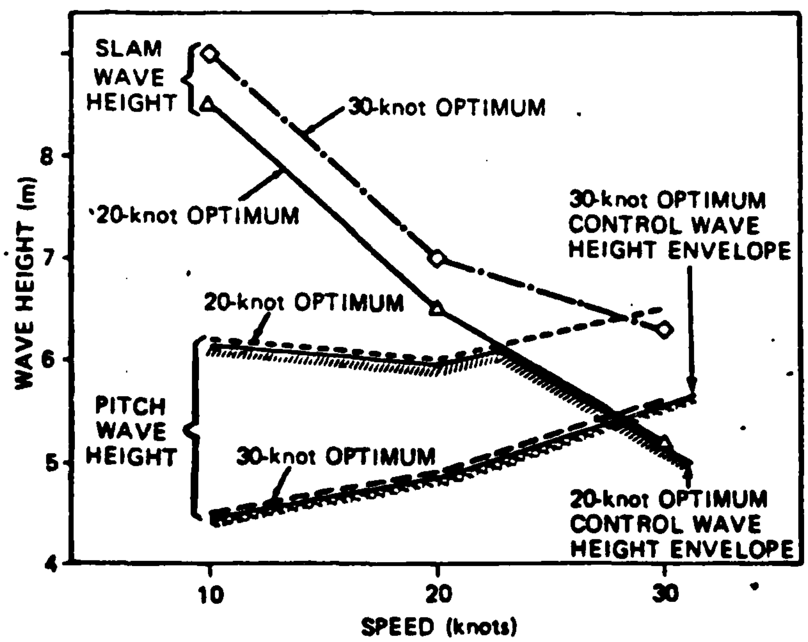

Figure 11 - Limiting Wave Height versus Ship Speed

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